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**BLASTING METHOD AND APPARATUS**

1           The invention relates to a blasting method for cleaning surfaces, wherein a carrier  
5           gas is supplied under pressure through a blasting line to a blasting nozzle, and liq-  
          uid CO<sub>2</sub> is supplied through a feed line, is transformed into dry snow by expansion  
          and is fed into the blasting line, as well as an apparatus for carrying out this  
          method.

10           A blasting method of this type has been disclosed in US 5 616 067 A. The CO<sub>2</sub> is in-  
          troduced in liquid form into an annular chamber which surrounds the blasting line  
          through which compressed air is passed, and from there the CO<sub>2</sub> is fed into the  
          blasting line through a circular array of converging capillaries, so that the expansion  
          occurs only upon entry into the blasting line. The dry snow thus created is entrained  
15           and accelerated by the compressed air and is jetted onto the workpiece to be cleaned  
          via the blasting nozzle. This method is particularly intended for gently cleaning pres-  
          sure-sensitive surfaces in such as electronic circuit boards.

20           US 5 679 062 describes a blasting method in which gaseous or liquid CO<sub>2</sub> or a mix-  
          ture of gas and liquid is expanded at the outlet of a nozzle and is introduced into an  
          enlarged vortex chamber in which a part of the gaseous and/or liquid CO<sub>2</sub> is trans-  
          formed into dry snow. The outlet of the vortex chamber is directly coupled to the  
          blasting nozzle. Here, the carrier gas is formed by the gaseous CO<sub>2</sub> that has been  
          supplied or is produced through evaporation.

25           US 5 725 154 A describes a blasting method in which dry snow is produced by ex-  
          panding liquid CO<sub>2</sub> by means of an expansion valve. Through a thin tube which is  
          coaxially surrounded by a tube for supplying the carrier gas, the dry snow is sup-  
          plied to a blasting pistol which then jets out in a mixture of carrier gas and dry snow.

30           WO 00/74 897 A1 discloses a blasting apparatus in which liquid CO<sub>2</sub> is supplied via  
          a capillary which opens into a conically divergent nozzle the diameter of which in-  
          creases towards the outlet to approximately three times the diameter of the capillary.  
          This nozzle is surrounded by an annular Laval nozzle in which the carrier gas that  
          has been supplied under pressure is accelerated to supersonic speed. The mouths of  
35           the CO<sub>2</sub> nozzle and the Laval nozzle are level with one another, so that two concen-  
          tric jets are produced, i. e. an inner jet consisting mainly of dry ice and a jacket jet  
          which is to accelerate the dry ice outside of the nozzle.

1 Also in applications in which larger surfaces such as the internal surfaces of pipes or  
boilers in industrial equipment shall be freed of firmly adhering incrustations, the  
use of dry ice or dry snow as blasting material, depending on the type of incrusta-  
tions, is frequently desirable, because the low temperature of the dry ice or dry snow  
5 makes the material to be removed more brittle. When particles of dry snow penetrate  
into the layer to be removed with sufficient kinetic energy, a cleaning effect is  
achieved by the fact that the particles of dry snow, when penetrating into the layer to  
be removed, are evaporated abruptly and thus blow off parts of the layer to be re-  
moved. Another advantage is that no additional means are necessary for discharging  
10 the used blasting material, because the dry snow evaporates to gaseous CO<sub>2</sub>.

However, the blasting methods described above are not suitable for these kinds of  
application, because the achievable volume flow rates and jet speeds are not suffi-  
cient and/or because dry snow is not produced in a sufficient amount or does not  
15 have the correct composition, so that the kinetic energy of the particles of dry snow  
is too small.

For this reason, for cleaning larger, heavily contaminated surfaces, blasting equip-  
ments have heretofore been used in which dry ice or dry snow is stored in solid form  
20 in suitable cooling tanks and is metered into the flow of compressed air. The com-  
pressed air and the dry snow serving as blasting material are then delivered together  
through a pressure hose which connects the blasting equipment to the blasting noz-  
zle. However blasting methods and apparatus of this type require cumbersome in-  
stallations and correspondingly high equipment costs as well as high expenses for  
25 storing the dry snow.

It is therefore an object of the invention to provide blasting methods and blasting ap-  
paratus in which high blasting powers and high cleaning effects can be achieved with  
little effort.

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This object is achieved with the features indicated in the dependent claims.

According to the invention, in a method of the type indicated in the opening para-  
graph, the CO<sub>2</sub> is supplied from the feed line into the blasting line via an enlarged  
35 expansion volume.

1 Surprisingly, it has been shown that, by suitably dimensioning the expansion volume  
and/or by suitably conducting the method, it is possible to create large amounts of  
dry snow having a high cleaning effect. In particular, it is possible with this method  
to achieve high flow rates of 0.75 to 10 m<sup>3</sup>/min or more, so that even larger or heav-  
5 ily contaminated surfaces can be cleaned efficiently. Since the dry snow serving as  
the blasting material is created from liquid CO<sub>2</sub> only at the time when the blasting  
method is practised, it is possible to save the high costs for the blasting equipment  
and for storing the dry snow, which have heretofore been necessary.

10 According to one embodiment, the production of strongly abrasive dry snow or dry  
ice is achieved simply by providing an expansion volume with sufficiently large vol-  
ume. In experiments it was possible to multiply the cleaning effect by increasing the  
expansion volume, when the other conditions were left unchanged. This surprising  
phenomenon is presumably due to the fact that the larger expansion volume between  
15 the mouth of the feed line and the point of entry into the blasting line leads to a tem-  
porary reduction of the flow velocity and hence to an increased particle density, so  
that the finely dispersed dry snow particles that are at first created upon expansion  
agglomerate or condense to larger particles before they are entrained by the flow of  
the carrier gas. This leads to the production of snow particles which have a larger  
20 mass and then produce a high cleaning effect because of their higher kinetic energy.

For the volume V of the expansion volume in relation to the cross-sectional area A of  
the feed line for the liquid CO<sub>2</sub> the following relation should be observed:

25 
$$V^{1/3}/A^{1/2} > 3 \text{ or preferably } V^{1/3}/A^{1/2} > 10.$$

Alternatively, the volume V of the expansion volume may be given in relation to a  
flow rate  $\phi$  of liquid CO<sub>2</sub>. In this case, the relation which should be observed is:

30 
$$V/\phi > 0.2 \text{ m}^3 \text{ s/kg, preferably } V/\phi > 0.6 \text{ m}^3 \text{ s/kg}.$$

The method may also be practised with a smaller volume of the expansion volume, if  
the smaller volume is compensated for by a larger pressure and a correspondingly  
increased flow rate of the carrier gas and/or if the expansion volume has a sufficient  
35 length, for example a length at least 15 or 30 mm.

1 The temperature prevailing in the expansion volume is considered to be an important  
factor for the production of strongly abrasive particles of dry ice. This temperature  
should preferably be low, preferably below  $-40^{\circ}\text{C}$ . When the method according to the  
invention is practised with a sufficient flow rate of carrier gas (e. g.  $0.75\text{ m}^3/\text{min}$ ) and  
5 when the flow rate of liquid  $\text{CO}_2$  is in an optimal ratio to the flow rate of air, e. g. in  
the order of magnitude of  $0.1$  to  $0.4\text{ kg CO}_2$  per  $\text{m}^3$  carrier gas (volume under atmos-  
pheric pressure), the cooling effect caused by the evaporation of  $\text{CO}_2$  appears to be so  
large that the expansion volume is kept on a sufficiently low temperature.

10 A good thermal insulation of the expansion volume permits to exploit the cooling ef-  
fect more efficiently and thereby to achieve the even lower temperatures in the ex-  
pansion volume and/or to reduce the expansion volume. Thus, according to another  
embodiment of the method, an expansion volume is thermally insulated from the en-  
vironment, so that the desired high cleaning effect can also be achieved with a small  
15 volume of the expansion volume and small flow rates. Here, it has been found to be  
advantageous that the feed line for liquid  $\text{CO}_2$  is also thermally insulated from the  
environment and has a good thermal contact with the walls of the expansion volume  
(e. g. by means of a heat exchanger), so that the liquid  $\text{CO}_2$  is pre-cooled already to  
some extent in the feed line.

20 It has been found in experiments that a relatively strong crust of dry ice is deposited  
already after a short time of operation on the walls of the expansion volume and/or  
the walls of the blasting line, and the crust may even extend into the blasting nozzle.  
This crust of dry ice improves the thermal insulation and cooling of the expansion  
25 volume and may also contribute directly to the creation of relatively coarse and hard  
particles of dry ice having a high cleaning effect. When the dry snow which is first  
produced by expanding the liquid  $\text{CO}_2$  is swirled, it impinges onto the walls of the ex-  
pansion volume and/or the blasting line with high velocity, so that the above-men-  
tioned, relatively strong and condensed crust is built-up there. On the other hand,  
30 the supply of heat via the walls of the expansion volume and the blasting line and  
the sublimation of  $\text{CO}_2$  caused thereby tends to loosen the crust. Thus, the crust fi-  
nally assumes an inhomogeneous, granulated and relatively brittle structure, with  
the result that the carrier gas passing-by with high speed permanently erodes coarse  
dry ice particles from the crust, and these particles then form part of the blasting  
35 material.

1 The desired production of such a crust of dry ice can be brought about or assisted by  
the presence of swirl edges in the flow path and by the swirling of the dry snow  
caused thereby. Thus, according to another embodiment of the invention, the blast-  
ing apparatus has at least one swirl edge in the flow path between the mouth of the  
5 feed line for the liquid CO<sub>2</sub> and the blasting nozzle. This swirl edge may for example  
be formed at the transition point between the expansion volume and the blasting  
line, when the expansion volume opens laterally into the blasting line. Moreover,  
such swirl edges may also be formed by an internal threading in a pipe section form-  
ing the expansion volume or by stationary or moveable internal structures such as a  
10 propeller wheel, a worm or the like in the expansion volume.

Suitable for executing the method is also a blasting apparatus having a source of liq-  
uid CO<sub>2</sub>, an expansion nozzle connected to said source for generating dry snow, and  
a blasting nozzle connected to a pressure source and converging towards a constric-  
15 tion and diverging from the constriction for accelerating the dry snow, wherein the ex-  
pansion nozzle is arranged upstream of the constriction.

Useful detailed and further developments of the invention are indicated in the de-  
pendent claims.

20 It has been found to be advantageous when the expansion volume enters into the  
straight blasting line at an angle of about 10 to 90°, preferably 20 to 45° in the flow  
direction. With this configuration, the flow of the carrier gas produces a certain drag,  
and the dry snow is gently deflected into the flow direction in the blasting line. Since  
25 the flow of the carrier gas in the blasting line has a component transverse to the lon-  
gitudinal direction of the expansion volume, it is to be expected that a vortex is cre-  
ated at least in the downstream portion of the expansion volume, which vortex pro-  
longs the dwell time of the dry snow in the expansion volume and hence the agglom-  
eration and the growth, respectively, of the particles and the crust, respectively, of  
30 dry ice. When the diameter of the blasting line is small, the angle of entry is prefera-  
bly more acute in order to prevent the dry ice from impinging onto to the opposing  
wall of the blasting line.

In a suitable embodiment, the point of entry of the expansion volume into the blast-  
35 ing line is located in a small distance upstream of the blasting nozzle.

- 1 The blasting nozzle preferably has a constriction, so that the carrier gas and the blasting material are accelerated to high speed.

Particularly preferred is the configuration of the blasting nozzle as a Laval nozzle in which an acceleration to approximately sonic speed or supersonic speed is achieved. The distance between the point of entry of the expansion volume into the blasting line and the constriction of the blasting nozzle should preferably be larger than the diameter of the blasting line.

- 10 When dimensioning the Laval nozzle, it should be taken into account that the supply of dry ice immediately upstream of the nozzle reduces the temperature of the medium and increases the density thereof, which causes a shift in the working point of the Laval nozzle. In order to achieve an optimal cleaning effect, in the method according to the invention, the cross-sectional area of the constriction of the Laval nozzle should be selected larger than it would be selected in the case that the medium is supplied with like pressure and like flow rate only via the blasting line. Moreover, the sublimation of dry snow increases the gas volume and leads to an acceleration of the flow of gas before, in or behind the constriction of the nozzle. Depending on the pressure conditions, droplets of liquid CO<sub>2</sub> may also enter into the blasting line or the blasting nozzle and evaporate there. By regulating the flow of carrier gas, the position where this evaporation and/or sublimation takes place can be adjusted such that an optimal jet speed is achieved.

When the flow rate of the carrier gas is too large so that a high dynamic pressure is built up in front of the blasting nozzle, the amount and the cleaning effect of the generated dry snow is reduced. It is therefore convenient to provide a metering valve in the blasting line upstream of the point of entry of the expansion volume, for optimally adjusting the flow rate of the carrier gas. Preferably, another metering valve is provided in the feed line for liquid CO<sub>2</sub> immediately at the point of entry into the blasting apparatus, so that the ratio of flow rates of carrier gas and CO<sub>2</sub> may be adjusted immediately at the blasting apparatus.

All the measures discussed above may suitably be combined with one another.

- 35 In a useful further development of the method, a small amount of water or of another solid or liquid blasting material (e.g. solid dry ice pellets) is injected into the flow of

1 carrier gas and/or into the expansion volume in order to further enhance the cleaning effect.

Embodiment examples will now be explained in conjunction with the drawings, in  
5 which:

Fig. 1 shows a sectional view of a blasting apparatus for carrying out the method according to the invention;

10 Fig. 2 is a sectional view of a blasting apparatus according to modified embodiment;

Fig. 3 shows an enlarged detail of figure 2;

15 Fig. 4 is a schematic sectional view of a blasting line which tapers step-wise, and

Figs. 5 to 7 show sectional and front views of a nozzle of the blasting apparatus.

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As is shown in figure 1, a blasting line 10 is formed by a straight cylindrical pipe which has an internal diameter DL of 39 mm. An inlet port 12 of the blasting line is connected to a compressor which has not been shown and from which compressed air is supplied with a pressure of 1.1 MPa, for example. The blasting nozzle 14 configured as a Laval nozzle is coupled to the mouth of the blasting line 10. The blasting  
25 nozzle has a convergent section 16 the internal diameter of which decreases from 32 mm at the upstream end to 12.5 mm at a constriction 18, and a divergent section 20 the internal diameter of which increases from the constriction 18 to 19 mm at the downstream end. The total length LL of the blasting nozzle is 224 mm. The length LC  
30 of the converging section 16 is 83 mm.

A connecting sleeve 22 between the blasting line 10 and the Laval nozzle 14 has an internal diameter of approximately 32 mm, corresponding to the upstream diameter of the blasting nozzle.

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Immediately upstream of the connecting sleeve 22 the pipe forming the blasting line 10 has a branch 24 which enters into the blasting line 10 at an angle of 45° in flow

1 direction. The distance D between the branch 24 and the upstream end of the blast-  
ing nozzle 14 is approximately 66 mm. A metering valve 26, a ball valve for example,  
is arranged in the blasting line 10 upstream of the branch 24. A tubular transition  
piece 28 is screwed into the branch 24, and the upstream end of the transition piece  
5 is connected to a flexible feed line 32 for liquid CO<sub>2</sub> through an adapter 30.

The feed line 32 is connected to a pressure bottle, which has not been shown and  
which accommodates an amount of CO<sub>2</sub> under such a pressure that the CO<sub>2</sub> re-  
mains liquid at environmental temperature. This pressure amounts to approximately  
10 5.5 MPa, for example, for an environmental temperature of 20° C. The feed line 32  
has an internal diameter of 3 mm. The liquid CO<sub>2</sub> exits through the feed line 32 due  
to the differential pressure, without any need for active displacement means. The  
flow rate is limited by the small cross section of the feed line 32.

15 The transition piece 28 forms an expansion volume 34 which has two sections 36, 38  
with different diameters. The upstream section 36 directly adjacent to the feed line  
32 has an internal diameter DC1 of 20 mm and a length L1 of 85 mm. The down-  
stream section 38 adjoins via a short conical section and has an internal diameter  
DC2 of 32 mm and a length L2 of 105 mm. The total length LE of the expansion vol-  
20 ume 34 is thus 190 mm. The branch 24 has an internal diameter DC3 of 39 mm,  
identical with the internal diameter DL of the blasting line 10.

At the point in the adapter 30 where the feed line 32 opens into the expansion vol-  
ume 34, the liquid CO<sub>2</sub> can expand abruptly. This causes a part of the CO<sub>2</sub> to be  
25 evaporated. The evaporation and decompression leads to a reduction in temperature,  
so that another part of the liquid CO<sub>2</sub>, which is finely dispersed at entry into the ex-  
pansion volume, condenses to fine particles of dry snow. Since the cross-sectional  
area of the upstream section 36 of the expansion volume 34 is approximately 44  
times the cross-sectional area of the feed line 32, the mixture of gaseous CO<sub>2</sub> and  
30 dry snow passes through the upstream section 36 of the expansion volume at mod-  
erate speed. At entry into the downstream section 38 the speed is reduced further.  
During the travel through the comparatively long expansion volume 34 the fine parti-  
cles of dry snow may aggregate to larger particles (agglomeration). Since the flow ve-  
locity decreases upon entry into the downstream section 38 and, accordingly, the dy-  
35 namic pressure increases, the particles may also grow to some extent through re-  
condensation of gaseous CO<sub>2</sub>. Thus, at entry into the still larger branch 24, rela-  
tively large dry snow particles have formed, which are now sucked by the drag of the



1 compressed air passing through the blasting line 10 and are entrained towards the  
blasting nozzle 14. In the blasting nozzle 14, the compressed air and the dry snow  
are accelerated to high speed, possibly to supersonic speed, so that a jet with high  
cleaning efficiency exits from the blasting nozzle. When this jet impinges on a surface  
5 to be cleaned, the dry snow acts as a blasting material for efficiently cleaning the  
surface.

Experiments have shown that the cleaning effect of the jet that has been generated in  
this way depends on the dimension of the expansion volume 34 and on the flow rate  
10 of compressed air in the blasting line 10. Without expansion volume, the cleaning ef-  
fect is significantly reduced. Likewise, the cleaning effect is reduced dramatically  
when the flow rate of compressed air in the blasting line 10 is too large. For this rea-  
son, the flow rate is so adjusted by means of the metering valve 26 that an optimal  
production of dry snow and an optimal cleaning effect are achieved.

15 The embodiment example described above may be modified in various ways.

It is possible for example to use an angled blasting line instead of the straight blast-  
ing line 10, so that the expansion volume and the upstream section of the blasting  
20 line merge symmetrically into the downstream section of the blasting line. An ar-  
rangement in which the blasting line 10 is enlarged to an annular space which coaxi-  
ally accommodates the expansion volume, is also conceivable.

In another embodiment, a hose section of considerable length may be provided be-  
25 tween the point where the expansion volume opens into the blasting line, and the  
blasting nozzle 14.

In order to produce increased amounts of dry snow, it is possible to have a plurality  
of feed lines 32 entering into the blasting line 10 via respective expansion volumes.  
30 The points of entry of the expansion volumes into the blasting line may be distrib-  
uted over the periphery of the blasting line and/or may be offset in axial direction. It  
is also possible to have a plurality of feed lines 32 opening into a common expansion  
volume.

35 Instead of compressed air, another carrier gas may be supplied via the blasting line  
10. Another blasting material may be added to this carrier gas or to the compressed  
air. Likewise is it conceivable to have additional solid or liquid blasting media enter-

1 ing into the blasting line via lateral feed lines upstream or downstream of the branch  
24 or possibly also into the expansion volume 34.

5 Figure 2 shows a blasting apparatus according to a modified embodiment. Here, the  
expansion volume 34 is formed only by the interior of the branch 24. This branch  
has an internal threading 40 into which the adapter 30 has been screwed-in. A me-  
tering valve 42 is provided in the feed line 32 at a small distance upstream of the  
adapter 30, so that the flow rate of liquid CO<sub>2</sub> may be adjusted. A flow rate of liquid  
10 CO<sub>2</sub> of approximately 0.1 to 0.3 kg per m<sup>3</sup> carrier gas (air) has proved to be a favour-  
able setting (the flow rate of carrier gas is given as the volume of carrier gas under at-  
mospheric pressure).

The portion of the blasting line 10 which includes the branch 24, and the portion of  
the feed line 32 directly adjacent to the adapter 30 are embedded in a sheath of ther-  
15 mally insulating material which has been shown in dotted lines in the drawing. This  
facilitates not only the handling of the pistol-type blasting apparatus but also im-  
proves the thermal insulation of the expansion volume 34 and the portion of the feed  
line adjacent thereto, so that a low temperature in the expansion volume is achieved.

20 In figure 3, the branch 24 has been shown in an enlarged scale. It can be seen that  
the internal threading 40 extends beyond the adapter 30 and forms a part of the in-  
ternal wall of the expansion volume 34. The flow path for the dry snow from the  
mouth of the feed line 32 into the blasting line 10 is limited by a number of swirl  
edges. A first swirl edge is formed directly by the abrupt increase in cross section  
25 from the feed line 32 to the internal cross section of the expansion volume 34 at the  
internal surface of the adapter 30. Other swirl edges are found at the point of entry  
of the branch 24 into the blasting line 10. Moreover, the grooves of the internal  
threading 40 also act as swirl edges. These swirl edges cause the dry snow forming in  
the expansion volume 34 to swirl, and especially the internal threading 40 promotes  
30 the adhesion of dry snow at the walls of the branch 24, so that a relatively compact  
but brittle crust 46 of dry ice is formed in the expansion volume and to some extent  
also in the blasting line 10. The CO<sub>2</sub> which is spayed out of the feed line 32 and is  
evaporated thereby forces its way through the crust of dry ice. This CO<sub>2</sub> and the car-  
rier gas flowing at high speed through the blasting line 10 and past the crust 46 per-  
35 manently erode small particles of dry ice from the crust. These relatively coarse and  
hard particles then form a very efficient blasting material by which a high cleaning  
effect of the blasting apparatus is achieved. The particles of dry ice may even grow

1 further on their way through the blasting nozzle 14, because they are swept and ac-  
celerated by the carrier gas which contains finer particles of dry snow. The exact lo-  
cation where the agglomeration of dry ice and the formation of the crust 46 takes  
place depends on the specific conditions and may shift (in both directions) more or  
5 less into the blasting line 10 and possibly into the blasting nozzle 14.

In the example shown, the expansion volume 34 has the same internal diameter as  
the blasting line 10, it may however have a smaller internal diameter, if desired.  
The angle at which the branch 24 merges into the blasting line 10 may also be var-  
10 ied, preferably in a range between 20 and 45°.

In the example shown in figure 2 the length LE of the expansion volume (measured  
on the central axis) is approximately 49 mm, and the diameter DC3 of the expansion  
volume is 32 mm. Then, the expansion volume 34 has a volume V of approximately  
15 39 cm<sup>3</sup>. When the feed line 32 has an internal cross-sectional area of 7 mm<sup>2</sup>, corre-  
sponding to a diameter of 3 mm, the ratio  $V^{1/3}/A^{1/2}$  is approximately 12.8. In prac-  
tise, the air flow rate through the blasting line 10 is preferably between 3 and 10 m<sup>3</sup>/  
min, with an optimum at about 5.5 m<sup>3</sup>/min. For a CO<sub>2</sub>/air ratio of 0.3 kg/m<sup>3</sup>, the  
corresponding flow rates  $\phi$  of CO<sub>2</sub> are approximately 0.0015 kg/s to 0.05 kg/m<sup>3</sup> and  
20 0.023 kg/s, respectively, for the optimum. The corresponding values for the ratio V/ $\phi$   
are then 0.0026 - 0.0008 m<sup>3</sup> s/kg and 0.0018 m<sup>3</sup> s/kg for the optimum. The con-  
striction 18 of the blasting nozzle 14 has a diameter of 13.1 mm.

In another embodiment, which has not been shown, the blasting line 10 has a  
25 smaller internal diameter of 12.7 mm, the diameter DC3 of the expansion volume 34  
is also 12.7 mm, and the length LE of the expansion volume is approximately 37  
mm. In this case, the expansion volume has a volume V of about 4.7 cm<sup>3</sup>. The air  
flow rate is then preferably between 1.5 and 2.5 m<sup>3</sup>/min. When the CO<sub>2</sub>/air ratio is  
again 0.3 kg/m<sup>3</sup>, one obtains a value between 0.00062 and 0.00037 m<sup>3</sup> s/kg for the  
30 ratio V/ $\phi$ . The value of  $V^{1/3}/A^{1/2}$  is in this case approximately 6.3. In this case the  
contraction 18 of the blasting nozzle 14 preferably has a diameter of 8 mm.

Under these conditions, supersonic speed can be reached downstream of the blasting  
nozzle 14.

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It is convenient to provide a baffle at the mouth of the blasting nozzle in order to re-  
duce the generation of noise.

1 Whereas, in the examples described above, the internal cross section of the blasting  
line remains essentially constant, embodiments are possible in which this internal  
cross section varies. For example, the internal cross section of the blasting line may  
be reduced in two steps, with smooth transitions, as is shown in figure 4. Possible  
5 positions for the branch 24 have also been shown in figure 4.

As will be understood from the examples given above, the expansion volume should  
not be too small and, in particular, should not have a too small length. In an embodi-  
ment which is presently considered to be preferable, the length of the expansion vol-  
10 ume is 100 mm or more.

Whereas the feed line 32 has an internal diameter of 3 mm in the shown embodi-  
ments, other embodiments are possible, in which the feed line 32 upstream of the ex-  
pansion volume 34 or preferably at the point of entry into the expansion volume has  
15 a diameter of only 1.0 or 1.3 mm.

For supplying liquid CO<sub>2</sub> via the feed line 32, optionally, a cold tank may be provided  
in which the CO<sub>2</sub> is kept liquid at a temperature of approximately -20° C and at a  
pressure of less than 2.2 MPa, e. g. 1.8 MPa.

20 Figures 5 to 7 show a modified embodiment of the blasting nozzle 14, which has the  
function of a Laval nozzle but is configured as a flat nozzle and permits to create a  
fan-like divergent jet having a relatively uniform density and velocity profile over its  
width. This blasting nozzle has, on the upstream end, a cylindrical portion 14a with  
25 a length  $L_a$  and an internal diameter  $D_a$ , which is adjoined by a transition piece 14b  
with the length  $L_b$ . Adjoining on the downstream side is a flattened section 14c with  
a length  $L_c$  and a rectangular internal cross section. The transition piece 14b serves  
for adapting the cylindrical internal cross section of the section 14a to the rectangu-  
lar internal cross section of the section 14c. This rectangular internal cross section  
30 has an essentially constant width  $W$  and a height which increases from a value  $H_1$  at  
the constriction, at the end of the transition piece 14b to a somewhat larger value  $H_2$   
at the mouth. In this way, an increase in cross-sectional area in accordance with the  
principle of a Laval nozzle is achieved, although the width  $W$  is practically constant.  
If at all, the width  $W$  may increase slightly in the vicinity of the mouth.

35 In a practical embodiment, the blasting nozzle 14 according to figures 5 to 7 has the  
following dimensions:

1	La	=	55 mm
	Lb	=	55 mm
	Lc	=	130 mm
	Da	=	27 mm
5	W	=	45 mm
	H1	=	3,0 - 4,0 mm
	H2	=	7,5 mm

The following dimensions apply to another embodiment example:

10	La	=	34 mm
	Lb	=	76 mm
	Lc	=	130 mm
	Da	=	12 mm
15	W	=	16 mm
	H1	=	2,25 - 2,60 mm
	H2	=	3,75 mm.

The internal surface in the flattened section 14c has corrugations which, in the example shown, are formed by longitudinal ribs 14b. Such corrugations lead to a significant reduction of noise, especially in the supersonic mode.

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